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Stark effect in resonant coherent excitation of 2s electron of Li-like Fe^{23+} ions channeling in a Si crystal

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ABSTRACT

We measured resonant coherent excitation of a 2s electron of 83.3 MeV/u Fe^{23+} ions planar-channeling in the $(\bar{2}20)$ plane of the silicon crystal. A silicon surface barrier detector (SSD) was used as a crystal target in order to obtain information on the ion trajectory in the channel since the energy deposit (ΔE) to the SSD gives information on the ion trajectories where the resonant transitions occur. For the low ΔE, i.e., near the channel center, optically allowed 2s–3p transitions were much stronger compared with other transitions. Increasing ΔE, i.e., increasing the amplitude of ion trajectory, the optically forbidden 2s–3s transition rapidly became strong. On the other hand, the optically forbidden 2s–3d transitions did not become strong as rapidly as 2s–3s transition. Furthermore, it was found that the transition energies to the $n = 3$ states changed with ΔE. The shifts of the transition energies were consistent with the estimation for the energy levels of the Stark-mixed $n = 3$ states depending on the distance from the channel center.

1. Introduction

Fast ions passing through a single crystal feel temporally oscillating fields originating from the spatially periodic structure of the crystal. When one of the frequencies of the temporally oscillating fields matches with the energy difference between two electronic states of the ion, the ion can be resonant-coherently excited. This resonant excitation referred to as resonant coherent excitation (RCE) was first pointed out by Okorokov [1]. After several experimental trials, the clear observation of RCE was performed by Datz et al., where they observed the RCE as the decrease in transmission of fixed-charge-state channeling ions as a function of the ion energy [2]. Since then, the RCE phenomena have been intensively studied in axial-channeling, planar-channeling or surface-scattering conditions [3–15]. In particular, Azuma et al. have performed a series of RCE experiments using planar-channeling of heavy ions with several hundreds MeV/u for a decade [10–14] and they observed structured resonance profiles for H-like heavy ions due to the Stark mixing induced by the static planar-potential in the channels [10–13]. Recently, they found RCE under non-channeling condition (3D-RCE) [16] and succeeded in the observation of dressed-atom formation, the polarization control of excited states, and the selective production of doubly excited state, using 3D-RCE [17–19].

We reported the RCE of a 2s-electron of a 83.5 MeV/u Li-like Fe^{23+} ion under the planar-channeling condition in the $(\bar{2}20)$ plane of the silicon crystal [15]. The resonances corresponding to optically forbidden transitions to 3s and 3d states were observed as well as those corresponding to the optically allowed transitions to 3p states. As a possible reason for clear observation of the optically forbidden transitions, we considered that the transitions to the 3s and 3d states are caused through the 3p-components in the Stark-mixed states with 3s and 3d components. This effect is very small at the channel center and becomes important with increasing distance from the channel center, reflecting the increase of the static crystal field.

In order to obtain information on the position where the transitions occur, we measured charge states of ions emerging from the target in coincidence with the energy deposit to the crystal target which is a thin silicon surface barrier detector (SSD). This method was applied for the trajectory-dependent RCE of 390 MeV/u Ar^{17+} ions planar-channeling through a silicon crystal [10,11]. The

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energy deposit to the crystal target by the channeling ions strongly depends on their oscillating trajectories and increases with the oscillation amplitude. Therefore, coincidence measurement of the energy deposit with the final charge state gives information on the position where excitation occurs.

2. Experiment

The transition energy, E_{trans}, due to the oscillating crystal field is obtained by multiplying the Planck constant and the frequency of the oscillating field in the projectile frame as

$$E_{trans} = hc\gamma\beta\left(\frac{k\cos\theta}{A} + \frac{l\sin\theta}{B}\right), \tag{1}$$

where θ is an incident angle between the beam direction and the [001] axis of the Si crystal in the $(\bar{2}20)$ plane, β is the ion velocity divided by the speed of light, γ is a Lorentz factor represented by $1/\sqrt{1-\beta^2}$, and h is the Planck constant. (A, B) is $(a, a/\sqrt{2})$ with the lattice constant of silicon, a. k and l are integers which show resonance indices. As shown by Eq. (1), the resonant excitation was observed by changing the incident angle θ in the $(\bar{2}20)$ plane.

A beam of 83.3 MeV/u Li-like Fe^{23+} ions was provided at RIKEN Ring Cyclotron (RRC). The transport elements of the beamline from the RRC to the target chamber were carefully tuned to reduce the angular divergences of the ion beam. The beam was collimated with a 3 mm thick tungsten plate with a hole of 0.5 mm diameter about 45 cm upstream of the Si crystal target. The beam optics calculation shows that the longitudinal momentum spread of the incident beam should be $\Delta p/p \sim 10^{-4}$ in full width. The beam intensity was about 500 ions/s in the present experiment.

A totally depleted SSD was adopted as a crystal target, the silicon thickness of which is 9.8 µm. We prepared the SSD by ourselves. Au (~100 Å) with a WO_3 layer (~ 100 Å) and Al (~100 Å) electrodes are plated on the entrance and the exit of the SSD, respectively. The crystal orientation was specified using a X-ray diffraction technique but precise evaluation of the crystal quality was not performed. The SSD was mounted on the high-precision goniometer so that the beam direction was near the [001] axis of the silicon crystal. The energy scale of the SSD output was calibrated by a ΔE–E coincidence measurement of energy deposit in the SSD with energy after passing through the SSD using α-particles from a ^{241}Am source, where the energy loss in Au with the WO_3 layer and Al electrodes of the SSD was taken into account. The resolution of the SSD was experimentally estimated to be ~180 keV originating in the electrical noise.

The ions emerging from the target were deflected by a dipole magnet placed at the downstream of the target in order to analyze final charge states of the ions but the bending power of the magnet is not enough to measure the energy loss of the ions. A two-dimensional position sensitive detector (2D-PSD) was located at about 8 m downstream of the dipole magnet. The angular divergence of the beam is experimentally estimated to be several tens µrad or less by taking account of the distance from the collimator to the 2D-PSD and the spot size on the 2D-PSD without the target crystal. Survived Fe^{23+} ions and charge-changed Fe^{24+}, Fe^{25+} and Fe^{26+} ions were detected by the 2D-PSD. The charge state, $q+$, and the energy deposit, ΔE, were simultaneously accumulated by a list-mode data acquisition at each incident angle, θ. The number of ions, $N^{q+}(\theta, \Delta E)$, with the charge state, $q+$, and the energy deposit, ΔE, was obtained from the accumulated data at each incident angle θ.

3. Results and discussion

During the passage of the crystal, an electron in the $n = 3$ or higher states is more easily ionized than that in the 2s state. Therefore, the survival fraction of Li-like ions, $f^{23+}(\theta) = \int f^{23+}(\theta, \Delta E) d\Delta E$, decreases when the 2s electron of Li-like ion is resonantly excited. The differential survival fraction, $f^{23+}(\theta, \Delta E)$, is given by

$$f^{23+}(\theta, \Delta E) = \frac{N^{23+}(\theta, \Delta E)}{\sum_{q=23}^{26} N^{q+}(\theta)}, \tag{2}$$

where $N^{q+}(\theta) = \int N^{q+}(\theta, \Delta E) d\Delta E$. The charge-state dependence of the energy deposit was neglected here although the difference between Fe^{23+} and Fe^{26+} ions was estimated to be 11% by taking into account an effective charge for the energy loss of charge-frozen Fe^{23+} ions, 24.55, using a high-velocity limit approximation. However, it was found that Fe^{24+} ions were major species in the ΔE region where Fe^{23+} ions were observed. Thus, we judged that charge-state dependence of ΔE is not important for the analysis of the present results.

Figs. 1(i) and 2(i) show the survival fractions of Li-like ions, $f^{23+}(\theta)$, for $(k, l) = (1, 1)$ and $(k, l) = (1, 2)$, respectively, as functions of transition energy converted from θ using Eq. (1). We can find five

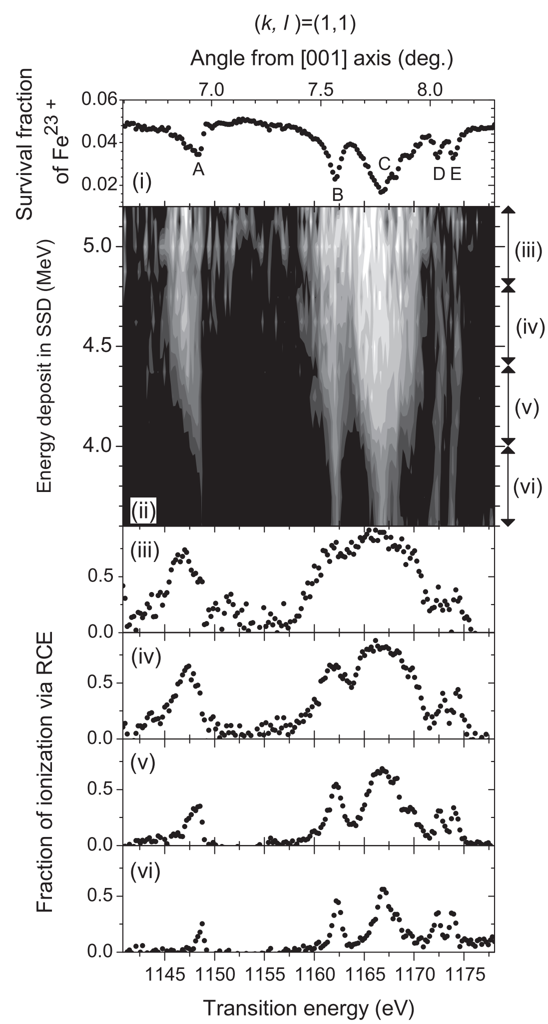

Fig. 1. (i) The survival fraction of Li-like ions is shown as a function of transition energy for $(k, l) = (1, 1)$. Dips A, B, C, D and E correspond to the transition to $3s_{1/2}$, $3p_{1/2}$, $3p_{3/2}$, $3d_{3/2}$ and $3d_{5/2}$ states, respectively. Angle from [001] axis θ is also shown on the upper abscissa. θ is transformed to the transition energy by Eq. (1). (ii) Contour map of the fraction ionized solely through RCE, $p^{23+}(\theta, \Delta E)$. It is shown as a function of the transition energy and the energy deposition, ΔE, for $(k, l) = (1, 1)$. (iii)–(vi) Sliced sections are shown for the regions of (iii) ΔE = 4.8–5.2 MeV, (iv) 4.4–4.8 MeV, (v) 4.0–4.4 MeV and (vi) 3.6–4.0 MeV, respectively.